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COLD REGIONS TECHNICAL DIGEST No. 90-1, DECEMBER 1990

USA Cold Regions Research and Engineering Laboratory
Hanover, New Hampshire 03755-1290

Lubricants at Low Temperatures

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Introduction

Lubricants represent the single most critical problem encountered by vehicles in cold regions. A vehicle lubricated for use in temperate regions will simply not operate in an extremely cold environment. A chunk of heavy gear oil can be used to pound nails at –40°C. Thus it is of the utmost importance to ensure that all lubricants used in the vehicle be chosen with low-temperature operation in mind, including engine oil, gear oil, grease, transmission fluid, hydraulic fluid and brake fluid. Lubricants must have a sufficiently low viscosity for low-temperature use and must also be able to diffuse over all surfaces requiring lubrication and to permeate the pores and surface cracks of metals. The use of unsuitable lubricants may result in channeling, dry gears and bearings, difficult starting and shifting, quick wear, and deterioration of engines, engine attachments and chassis.

There are three broad classes of lubricating fluids: petroleum-based mineral oils, synthetic hydrocarbons and silicones. Mineral oils are the easiest to produce, the least expensive and the most commonly used, especially in temperate areas. Synthetic lubricants are considerably costlier but are preferable in many applications because of their superior performance at high and low temperatures. Silicone-based lubricants are very expensive, but because of their excellent performance range and hydrophobic properties, they are valuable in some applications.

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Mineral oils

These are produced through distillation of a crude oil and are extremely heterogeneous in their make-up, containing a variety of hydrocarbons, aromatics and other molecular varieties. The composition will vary with the crude oil used, as will the properties of the oil to some extent. Paraffinic or straight-chain molecular oils are waxy, have high viscosity indices (VI)*, and begin to crystallize at relatively high temperatures, while naphthenic oils, containing many ring structures, have lower VIs and begin to crystallize at lower temperatures. In addition, because mineral oils are complex mixtures, they will have no sharply defined physical properties, such as pour point, flash point, etc. These properties depend to a great extent on the conditions surrounding the test and on the nature of the crude oil used. The behavior of these oils can be altered through the use of VI improvers, pour point depressants, etc., but there is a limit to the effectiveness of these additives. Nevertheless, petroleum-based products are widely used as engine lubricants, even in extremely cold environments, largely because of the need for frequent oil changes as a result of heavy sludge formation resulting from excessive idling and engine operation at temperatures below optimum. Infiltration of dust and grit is also a problem in some areas, such as the North Slope of Alaska and the McMurdo area of Antarctica. In any case, frequent oil changes can be prohibitively expensive if the higher-priced synthetic fluids are used.

Synthetic lubricants

These are made by polymerization of various short-chain base fluids, which results in a much more uniform product with narrow ranges of physical properties. In general they have improved volatility characteristics, improved oxidation and temperature stability, higher VIs, and better viscosity and temperature characteristics. They respond well to additive treatment and can be tailored for specific applications. Poly-α-olefins (PAOs) and various esters are commonly used as base fluids and yield oils with good VIs (up to 150). They are frequently used in cold regions as an engine oil, despite the higher cost, because of their good low-temperature performance. Synthetic fluids are commonly used as engine oils, hydraulic fluids, brake fluids, semi-fluid lubricants and various types of greases. They are especially valuable in applications where

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* The viscosity index is an indicator of the viscosity change with temperature. A low VI implies a relatively large change with temperature. The system was first set up using two arbitrarily chosen oils; one that changed greatly with temperature was assigned a VI of 0, and another that did not was assigned a VI of 100. Many oils today exceed this maximum.

extremely high temperatures are anticipated, such as in turbocharged engines, because of their excellent temperature stability.

Silicone lubricants

These are a specialized subset of the synthetic lubricants in which the backbone of the molecular chain is composed of a silicone-based polymer. The properties of these polymers are determined by the chain length and the nature of the side chains, either straight chain (usually methyl) or ring (usually phenyl). Silicone oils and greases have excellent temperature characteristics, high VIs and low surface tensions, allowing for superior penetration and coating of lubricated surfaces. They are nonhygroscopic and chemically inert. These lubricants are commercially available as brake and hydraulic fluids and as various sorts of greases. They are not recommended for steel-on-steel sliding lubrication but are very valuable in lubricating nonferrous metals, plastics, rubbers and combinations of these.

Engine oil

Engine oils must function effectively in the most demanding environment of any automotive lubricant. They must be able to withstand the extremely high temperatures in the combustion chamber while protecting the cylinders, pistons and rings from mechanical, abrasive and corrosive wear. They must also minimize the formation of deposits in the combustion zone and sludge in the crankcase. In low-temperature operations, sludge formation is particularly prevalent because of extensive idling and the resulting contamination of the crankcase oil by blow-by products, including water, gases and unburnt fuel. These contaminants can cause corrosion and varnishing of the crankshaft, connecting rods and camshaft bearings. Because of this, a vast amount of research has been devoted to developing means of producing superior base oils, improving their performance, and testing their relative effectiveness.

Important characteristics

Viscosity is the most important characteristic governing the behavior of engine oil and is influential in

- Starting and warm-up
- Power output and fuel consumption
- Engine cooling
- Starting wear
- Oil consumption
- Oil leakage
- Engine noise.

The first four items require a low-viscosity oil for optimum performance; the last three need a high-viscosity oil.

Viscosity is measured in various ways. A cold cranking simulator (CCS) is used to measure the dynamic viscosity (in centipoise) in low-temperature, high-shear conditions similar to those met during engine starting. The kinematic viscosity (in centistokes) measured at 100°C is used to determine the performance of the oil at the high-temperature, low-shear conditions of the engine in normal operation, and it reflects the ability of the oil to lubricate and protect moving engine parts at these elevated temperatures. The kinematic viscosity is also measured at 40°C. Using the values at these two temperatures, the viscosity–temperature behavior can be predicted to some extent. These three measures of viscosity are usually given in technical information on engine oils, along with the VI.

The pour point of an oil is usually given on technical data sheets and was formerly used to give some idea of the temperature at which the oil would be fluid to some degree. However, the pour point is nothing more than a temperature within 2.8°C of the solid point, which is the temperature at which the oil is completely gelled. Oil cannot be pumped at the pour point, and it will impart only a modest degree of lubrication, if any. The temperature rise required before effective lubrication is possible will vary between oils.

Borderline pumpability temperature (BPT) is sometimes given on technical data sheets describing low-temperature oils. This property reflects the ability of the oil to circulate readily throughout the engine. Failure to do so can result in serious engine damage. It is normally measured using a mini-rotary viscometer (MRV). Actual operational tests in a Cummins diesel engine suggest that values derived by this means may be quite misleading. First, there is a considerable difference between the actual pumpability of oils identical in every way except in the nature of the viscosity index improver (VII) additive. This BPT difference may be nearly 10°C. Second, the values obtained using the MRV showed virtually no difference between these oils and gave values over 20°C lower than the actual BPT in the operational tests (Machleder and Kopko 1989, Frame et al. 1989). Moreover, individual engines differ widely in their oil distribution systems design, which strongly affects their low-temperature performance. For example, in one system including a restriction orifice, the size of the orifice strongly influenced the time it took for oil to reach the bearings. At −25°C this took 90 s with a 1.5-mm orifice (and one test engine seized), while it took less than 40 s with a 2.0-mm orifice. Other influential factors are the oil screen design and the diameter and length of the oil pickup tube. In any case, an oil with pumping characteristics that are satisfactory in one engine may not be suitable for another.

Table 1. Properties of some typical base stocks. (From Roth 1989.)

	Mineral oils		*Synthetic oil*	
	Low natural pour point	*High natural pour point*	*PAO*	*Ester*
Viscosity at 100°C (cs)	4.01	3.96	3.89	4.82
Viscosity at 40°C (cs)	19.66	19.60	16.35	19.19
Viscosity index (VI)	100	94	136	136
CCS at −20°C (cp)	750	920	NA	NA
CCS at −25°C (cp)	1370	1770	520	840
CCS at −30°C (cp)	2670	3550	840	1375
Pour point (°C)	−21	−12	−69	−60

The volatility of the oil becomes increasingly important as the oil viscosity decreases, since this implies the presence of lighter fractions in the oil. The problem lies first in the possibility of these lighter fractions being driven off during normal operation resulting in an increase in BPT, etc., and second, in increased oil consumption. This problem is more pronounced in mineral oils than in synthetics.

Formulation

Engine oils are made using mineral oils, synthetic hydrocarbon oils, or a mixture of both. Table 1 compares a low-pour-point mineral oil, a high-pour-point mineral oil, and two types of synthetic oils. The low-temperature superiority of the synthetic oils is clear. The desirable properties of the chosen base oil are then enhanced through the use of additives, including a VII, a pour point depressant (PPD) and a detergent inhibitor (DI) package, which includes rust and corrosion inhibitors, antioxidants, metallic detergents and dispersants. Many different compounds are used in these roles. Since the additives in one oil may not be compatible with those in another similar oil, it is not a good idea to mix oils, as it is possible to reduce the effectiveness of one or several of these additives.

Engine oil classification systems

There are two principal systems for classifying engine oils: the API system and the SAE system.

The API classification system is based on the oil's performance characteristics in the intended type of service. Appendix A gives the API engine oil classifications for gasoline and diesel engines based on tests in selected engines under controlled conditions.

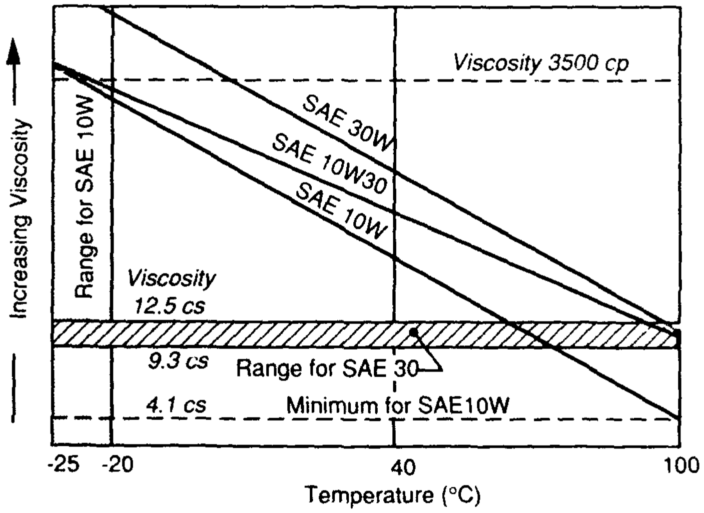
The SAE classification system grades oils according to their viscosity at 100°C and at various lower temperatures depending on the viscosity grade. There are 10 such grades as shown in Table 2.

Table 2. SAE viscosity grades for engine oils. (From Chevron USA, Inc. 1988.)

SAE viscosity grade	*Viscosity (cp) at maximum temperature (°C)*	*Maximum BPT (°C)*	*Viscosity (cs) at 100°C min*	*max*
0W	3250 at –30	–35	3.8	
5W	3500 at –25	–30	3.8	
10W	3500 at –20	–25	4.1	
15W	3500 at –15	–20	5.6	
20W	4500 at –10	–15	5.6	
25W	6000 at –5	–10	9.3	
20			5.6	9.3
30			9.3	12.5
40			12.5	16.3
50			16.3	21.9

The W grades reflect the low-temperature characteristics of the oil, as well as a minimum permitted viscosity at 100°C. The non-W grades are based only on their viscosity at 100°C. A multigrade oil (for example, 10W30) is one in which the low-temperature requirements are satisfied at the W level and the 100°C performance at the non-W level, implying a good VI or insensitivity to temperature. Figure 1 illustrates the effect of temperature on the viscosity of single-grade and multigrade oils. Multigrade oils are particularly valuable in cold regions where low pour points and low viscosities are necessary to ensure minimum engine wear on start-up and satisfactory lubrication at normal operating temperatures.

Table 3 lists a number of commonly used engine oils in order of their viscosity indices. Note that in terms of VI, the mineral oils are



1. Effect of temperature on the viscosity of single-grade and multigrade oils.

Table 3. Physical properties of some commercially available engine oils.

Brand	Product	Type	VI	SAE grade	API grade	Viscosity (cs) 40°C	Viscosity (cs) 100°C	BPT (°C)	Pour point (°C)
Mobil	Delvac 1200	Mineral	95	30	CE,CD-II CD,SG	98	11.8		–18
Mobil	Delvac 1200	Mineral	100	10W	CE,CD-II CD,SG	38	6.4	-25	–29
Chevron	RPM Delo Motor Oil	Mineral	103	30	CD,CD-II SF	106.9	12.1		–23
Chevron	RPM Delo Motor Oil	Mineral	115	10W		41.0	6.63		–34
Chevron	RPM Delo Motor Oil	Mineral	131	15W40	CE	105.5	13.8		–29
Mobil	Delvac 1200 Super	Mineral	135	15W30	CE,CD-II CD,SG	106	14.0	–20	–29
Mobil	Delvac 1300 Super	Mineral	135	15W40	CE,CD-II SG,SF	104	14.0	–25	–29
Mobil	Delvac 1300 Super	Mineral	137	10W30	CE,CD-II SG,SF	72	10.5	–30	–32
Emery	Emgard Universal SF-CD	Synthetic	152	5W30	CC,CD,SF	76.0	12.2	–39	–59
Emery	Frigid-Go	Synthetic	153	0W20	CC,CD,SF	30.1	6.1	-50	<–55
Conoco	High Performance	Synthetic	156	5W30	CC,CD, SG	72.8	11.7	-65	–55
Mobil	Delvac SHC Arctic	Synthetic	167	5W30	CD,SF	55.7	10.0		–54
Mobil	Delvac 1	Synthetic	187	5W40	CE,CD-II SF	86.0	15.0	–44	–51
Chevron	Sub-Zero Fluid	Synthetic	191	0W30	CC,CD,SE,SF	53.3	10.5		–54
Caterpillar	CPX Arctic Vehicle Oil	Partial synthetic	210	0W30	CD,SF	52.0	10.5	–43	–51

lower than the synthetics, single grades are lower than multigrades, and the pour points and borderline pumping temperatures tend to decrease with increasing VI. There are some mineral oils with excellent low-temperature characteristics and high VIs because of their additive packages. However, possible problems with volatility should be considered when using these oils.

Choice and use of engine oil

There are two schools of thought concerning choice of engine oils for extremely cold operations.

For the "business as usual" school the thinking is that it is best to use the manufacturer's recommended lubricants at all times on the grounds that the engine's internal temperature in the course of normal operations will be much the same throughout the year, regardless of the ambient temperature. A heavier oil will provide better lubrication for engine parts and bearings and will result in longer engine life. The assumption is that the engine will be kept sufficiently warm to start either through use of block and pan heaters or by storage in a heated garage. This would probably be the best approach for stationary engines such as generators or any other equipment that is run virtually continuously, provided such engines are housed in insulated enclosures.

The "lighten it up" school is the most widespread practice in cold regions, the idea being to use the lightest grade of oil the engine will tolerate. All machinery in cold regions is equipped with engine heaters of some sort; however, at extremely low ambient temperatures, they will usually not be able to bring the engine temperature up to the pour point of the heavier-grade oils. It is extremely important in these very low temperatures to use a pan heater as well as a block heater. Heating the engine block is effective for increasing the temperature of the oil on the cylinder walls, which will lower the oil viscosity and increase the maximum cranking speed. It does not, however, have a significant impact on the sump temperature. At very low temperatures, heating of the oil sump is also necessary since lubricants will gel and become incapable of providing adequate lubrication once cooled below a certain temperature. Heating the block may allow the engine to start, but if the oil in the sump is in a gelled state, it cannot lubricate the cylinders and bearings and the engine will quickly seize. The temperature at which this occurs depends on the specific lubricant used, but for winter lubricants it is generally below –25°C. The BPT figures given in Table 3 provide an idea of the likely behavior of various oils at low temperatures.

There are a number of commercially available engine lubricants useful down to at least –50°C. As a rule of thumb, if there is any

doubt as to the state of the oil in the crankcase before starting, do not attempt starting unless the oil drips off the dipstick. If it fails to do so, apply more heat.

Oil, engine, arctic (OEA), used by the military, is a synthetic 0W20 lubricant intended for temperatures from 40° to -50°C. This lubricant is also approved for use in power steering systems, hydraulic systems, and both automatic and standard transmissions. In response to concerns that such a light oil might not provide sufficient engine protection at higher temperatures, it was tested in a wide variety of military diesel equipment in temperate to hot conditions. It was found satisfactory in all tests. There were no oil-related failures and no excessive oil consumption. This suggests that while it may be desirable to change to a heavier-grade oil in the summer, no lasting harm will result from using lighter grades year-round.

Engine oil and filters should be changed every 2000 miles or 250 hours, especially if the equipment is idled heavily. This is primarily due to the accumulation of sludge and contaminants in extremely cold conditions. There is also strong evidence that the low-temperature properties of oil may change with use through degradation of the VII or other factors. Laboratory simulations have shown, for example, that diluting a multiviscosity oil (in this case, by unleaded gasoline) can lower the CCS viscosity significantly while affecting the MRV viscosity very little. This means that the engine will crank more easily, but pumpability will not be improved. This misleading situation can lead to increased engine wear or serious damage.

Oil treatments

A number of oil treatments are commercially available as additives for engine oil. Manufacturers' claims include reduced engine deposits, increased gas mileage, improved low-temperature performance, easier starting, reduced engine wear and so forth.

The most extravagant claims are made by producers of additives containing suspended polytetrafluoroethylene (PTFE, or Teflon), and in general these claims appear to be justified. These products contain microscopic particles of PTFE in a synthetic oil, which is added to the engine oil when the oil is changed. During operation the particles are deposited on metal surfaces where frictional motion is taking place. The resulting solid film provides excellent low-friction properties. This results in easier movement of engine parts, reduced engine wear, easier starting and decreased fuel consumption. There are reports that an engine treated with these additives can run for a short time without oil without damaging the engine. These fluids can also be added to gear oils and greases with similar effects.

Two-stroke engine oils

These oils are specifically formulated for the special requirements of two-stroke engines and should not be replaced with any other types of oils. They contain an ashless detergent, in contrast to most engine oils, which use a metallic detergent, and they are formulated using a base oil chosen to minimize deposit formation. The use of unsuitable oils will cause clogging of the exhaust ports, deposits in the combustion chamber, and fouling of the spark plugs.

The only known problem in the use of mixed-fuel two-stroke engines occurs in equipment in which the oil is injected from a separate reservoir rather than premixed in the fuel. In this case the oil at very low temperatures may be too viscous for proper injector operation, resulting in insufficient oil delivery and consequent engine damage. If this is likely to be a problem, the oil should be premixed with the fuel in proportions recommended by the manufacturer. There are two-cycle oils with pour points down to −60°C, but this temperature is well below that at which the oil can be pumped through the injector system and should not be taken as the minimum useful temperature of the oil in service.

Gear oil

Gear lubricants must be able to protect the surfaces of the gear teeth from the extremely high intermittent pressures developed in operation. The simplest way to accomplish this is to increase the viscosity. However, this introduces an element of drag, which, taken to extremes, would seriously reduce the amount of transmitted power. Thus, the design of an effective gear lubricant involves a trade-off between high viscosity and ease of movement. As in many lubricating applications, heat is generated in operation, and the lubricant must be effective at both the highest and lowest expected temperatures.

As with engine oils, two of the commonly used classification systems have been formulated by API (Table 4) based on application and SAE (Table 5) based on viscosity. Multigrade gear oils are available, and 75W90 synthetic gear oil is commonly used in cold regions, as is 75W, either mineral or synthetic. Thicker oil, such as 80W90, can be used in heavy equipment down to −40°C, but in this case the equipment must be moved very slowly initially to allow the oil to warm. If any piece of equipment feels stiff at first, it should never be forced.

Differentials, transfer cases and gear boxes in manual transmissions are seldom heated. At very low temperatures even 75W oil becomes very thick. Shifting gears becomes progressively more difficult as temperatures decrease. It often is impossible to shift from neutral until the transmission has been heated by internal friction or applied heat. Leaving the vehicle in gear before being

Table 4. API lubricant service designations for automotive manual transmissions and axles. (From Chevron USA, Inc. 1988.)

API designation	*Application*
GL-1	Spiral-bevel and worm gear axles and some manual transmissions under mild service
GL-2	Worm gear axles not satisfied by GL-1
GL-3	Manual transmissions and spiral-bevel axles under moderately severe service
GL-4*	Hypoid gears in normal severe service without severe shock loading
GL-5	Hypoid gears in severest service including shock loading
GL-6*	High offset hypoid gears in normal severe service

* Obsolete but still of commercial interest

Table 5. SAE gear oil classification. (From Chevron USA, Inc. 1988.)

SAE viscosity grade	*Temperature (°C) at Brookfield viscosity of 150,000 cp*	*Viscosity at 100°C (cs)* Minimum	*Maximum*
75W	−40	4.1	
80W	−26	7.0	
85W	−12	11.0	
90		13.5	<24.0
140		24.0	<41.0
250		41.0	

parked for any length of time is not adequate. If the lubricant is not sufficiently fluid, the gears will run dry.

This problem is less severe in vehicles with automatic transmissions, since these are commonly heated, and the transmission oil is lighter in any case. However, the differentials in these vehicles must be considered. There have been cases of drive lines twisting and gears breaking when thickened oil essentially immobilized the gears. For this reason it is very important to start off slowly in extreme low temperatures.

Table 6 shows some physical properties of some commercially available gear oils listed in order of VI. Note that the two mineral products show very high VIs. This is due to VII additives. Brookfield

Table 6. Properties of some SAE 75W90 gear oils.

Brand	*Product*	*Type*	*VI*	*Viscosity (cs)* 40°C	*Viscosity (cs)* 100°C	*Brookfield viscosity at –40°C (cp)*	*Channel point (°C)*	*Pour point (°C)*
Caterpillar	CPX Arctic Gear oil	Synthetic	150	106.0	14.7	110,000*		–48
Mobil	Mobilube SHC	Synthetic	150	106	15.2	100,000		–46
Conoco	High Performance	Synthetic	152	136.5	17.5	140,000	–45	–45
Chevron	Arctic Gear Lubricant	Mineral	170	91	14.6	140,000	–54	–40
Mobil	Mobilube HD Plus	Mineral	200	85		135,000	–46	–40

* at –42°C

viscometer measurements give the apparent viscosity of the oil in low-temperature use. Tests have suggested that, in general, axles can be damaged at viscosities greater than 150,000 cp. This may not be true for all axles but can be used as a guideline in choosing a gear lubricant. The channel point is the lowest temperature at which a gear lubricant can be used safely.

It is best to follow manufacturers' recommendations for manual transmission lubricants, as not all vehicles require heavy gear oils. Some foreign car manufacturers use engine oils routinely as the gear lubricant in the manual transmission. 0W30 engine oil is commonly used in this application for pick-up trucks and some large construction equipment in the Antarctic, where temperatures range from –60° up to +10°C. Some Arctic operators have used 10W mineral oil in gear boxes in extremely low temperatures. However, this is not recommended if a heavier gear oil is normally specified because of the excessive wear that is likely when the temperature either in the gears or the environment rises. A fairly common practice is to thin the existing gear oil with kerosene or some similar product. If this is done, the oil should be changed when the temperature rises. Thinning with one of the PTFE products may both thin the gear oil and improve the lubrication of the gear surfaces. Gear oil should be checked at the same time the engine oil is changed.

Grease

A grease is a two-phase material composed of a thickener in a liquid lubricant. In the majority of commonly used greases the thickener is a soap made from any of a variety of fatty acids and alkali elements, including calcium, lithium and aluminum. Water resistance, melting point and sealing ability of the grease are strongly influenced by both the nature of the fatty acid and the alkali

used in the soap. Other thickeners, such as clays or various polymers (e.g. polyureas), are used for some special cases or extreme environments.

The liquid lubricant phase may be a mineral, synthetic or silicone oil of almost any weight. The properties of the grease governed by this fluid component are evaporation losses, low-temperature behavior, and compatibility with the seal materials. As with other types of lubricants, greases containing synthetic oils have better low-temperature characteristics than those with mineral oils; silicone-based oils are best, although they may lack the lubricity of other types.

In addition to the thickener and fluid components, which constitute the greater part of the final product, additives may be included to improve certain properties, such as oxidation or rust inhibitors, pour point depressants and antiwear agents. Load-carrying and antiseize additives function either by reacting with or forming a protective coating on surfaces that experience high temperatures or loads. Molybdenum disulfide (MoS_2) is one example of an additive that is widely used in extreme-pressure applications, especially at low speeds, and it is often recommended by equipment manufacturers. In terms of the percent by mass, most greases contain 5–20% thickener, 65–95% lubricating oil, and 0–5% additives.

During manufacture the soaps form a three-dimensional structure containing the oil. Under low to moderate load, this structure causes the grease to behave as a solid. It will not flow under normal circumstances, but it will adhere to the surface to which it was applied. However, when an applied load is sufficient to overcome the structure, the grease will flow like an oil until the load is removed, at which time it will return to its original state. This eliminates the need for sophisticated sealing systems and is the principal advantage of using grease rather than oil. The disadvantages of greases are the relative difficulty of application and their poor heat transfer properties. However, the latter is only a serious consideration in high-speed applications, which do not ordinarily occur in automotive applications.

The most commonly used classification system for greases was developed by the National Lubricating Grease Institute (NLGI). This system (Table 7) is based on the consistency or softness of the grease. It is measured using a standard cone that is allowed to penetrate a sample of the grease under its own weight for 5 s, normally at 25°C. The depth of the penetration determines its NLGI rating. Values may be given for either worked or unworked samples. A worked sample is one that has been forced through a perforated plate for a given number of strokes (60 if the number of strokes is

Table 7. NLGI consistency grades for greases. (From Klamann 1984.)

NLGI grade	*Worked penetration (mm) at 25°C*	*Appearance*	*Applications*
000	44.5–47.5	Very soft, similar to	
00	40.0–43.0	very thick oil	Gear greases
0	35.5–38.5	Soft	
1	31.0–34.0		Greases for antifriction
2	26.5–29.5	Creamy	bearings
3	22.0–25.0	Almost solid	Water pump
4	17.5–20.5	Hard	greases
5	13.0–16.0	Very hard,	Black greases
6	8.5–11.5	like soap	

not given). The unworked value is useful in suggesting the magnitude of the break-away torque and the ease with which the grease can be dispensed or can travel through tubing in centralized lubrication systems.

In terms of low-temperature operation, greases suffer the same problems as oils: thickening and loss of lubricity. Since the thickener, on the whole, plays a minor role in the low-temperature characteristics of a grease, these difficulties are primarily a function of the lubricating oil. Technical specifications sheets usually give the viscosity of the oil phase, which can be used as a guide. However, it is best to use the grease manufacturers' guidelines on useful temperature range and recommended applications. Table 8 shows the characteristics of some low-temperature greases.

One of the primary problems with grease at low temperatures is applying it. Grease that is cold and stiff can be very difficult to pump, largely because of the small orifices involved. Large operations normally use heated lubrication trucks so that lubricants can be kept at a temperature at which they will flow. However, even with this advantage, difficulty is encountered with some equipment with centralized lubrication systems composed of small-diameter tubes of various lengths that are usually at ambient temperatures. This can be a serious problem since heavily used equipment may require greasing every 20–40 hours.

In some applications the grease can be softened by injecting a small amount of some light fluid such as kerosene into the grease nipples, for example, in crane pulleys. This practice should be used with care and moderation, and the grease should be replaced when

Table 8. Some commercially available low-temperature greases.

Brand	Product	Thickener	NLGI grade	Oil properties: Viscosity (cs) 40°C	Viscosity (cs) 100°C	Pour point (°C)	Worked penetration (0.1 mm at 25°C)	Useful range (°C)
Lubriplate	MAG-1	Lithium	1	26		–65	32	–50 to 150
Conoco	Low-temperature grease	Lithium	1	24	4.32	–65	325	–50*
Chevron	Avi-motive grease W	Polyurea acetate complex	1	18	3.8		325	–5 to 150
Lubriplate	Low temp	Anhydrous calcium	1.5				280–310	5 to 120
Dow Corning	33	Lithium	1.5				260	–75*
Mobil	Synthetic universal grease	Lithium complex	2	220	23.8		280	–3 to 230
Chevron	Avi-Motive grease	Polyurea acetate complex	2	32	5.1		280	–4 to 150
Emery	Frigid-Go Moly	Lithium complex	2	24.1	5.1	–80	285	–75*

* Upper limit not available

temperatures rise. Other fluids that can be used in a similar manner are PTFE-containing fluids used for oil treatment. These fluids can be mixed with grease before application. After a period of use, the PTFE coats the bearing surfaces and affords some degree of protection even when the grease itself is providing minimal lubrication. Available instrument greases are useful down to –75°C. These include silicone greases and PTFE-containing greases and are useful on high-speed bearings, speedometer cables and other light duties. Solid film lubricants based on molybdenum sulfide or PTFE offer excellent serviceability in certain applications and can provide lubricity down to cryogenic temperatures.

Automatic transmission fluid

Automatic transmissions have operated satisfactorily in field tests and are becoming increasingly common on light equipment as well as heavy construction equipment. Problems encountered with some of the earlier models have been eliminated, and newer types appear to suffer no more low-temperature damage than manual transmissions. Some operators prefer manual transmissions because they offer greater latitude of operation in experienced hands; however, the greater potential for damage in inexperienced hands mitigates in favor of automatic transmissions for most multiuser vehicles.

The two most prevalent fluids designed specifically for use in this application have been specified by GM and Ford. They differ in their behavior at very low clutch sliding speeds: GM fluids are designed for a low coefficient of friction as the clutch approaches lock-up, while Ford specifies a high coefficient. However, there are numerous transmissions made by other manufacturers, and lubricant recommendations vary widely. Manufacturers frequently suggest multigrade synthetic engine oils, including such light-weight oils as 0W20. It is important to follow the manufacturers' recommendations because of the wide variety of transmissions and torque converters with differing constraints. It is not a good idea to add PTFE-containing products to automatic transmission fluid, as the transmission relies on a certain amount of friction to function. Reducing it will result in improper operation in most cases.

In addition to petroleum-based fluids, there are commercially available silicone fluids that can be used in some automatic transmissions. The useful temperature range of these fluids extends far below any naturally occurring low temperatures. It is fairly easy to heat an automatic transmission, and if this is done, there should be little difficulty encountered in low-temperature operations.

It is a good idea to allow the transmission to operate for a short time without a load. This is accomplished by shifting into neutral so that the oil can be worked somewhat before starting out. Some Arctic veterans suggest parking so that the vehicle can be driven away straight forward after it has been parked overnight, leaving the shift in neutral, so that the pump is not strained by being forced through reverse on the way to drive when the oil is stiff. In addition, the power steering system will not be called upon for maximum output before the power steering fluid has been warmed.

Hydraulic fluid

There is a dizzying variety of hydraulic fluids in common use, ranging from water-miscible types through petroleum-based products to silicone fluids. For most low-temperature hydraulic applications, water-containing fluids are not suitable, and silicone fluids are too expensive. Manufacturers' recommendations should be followed when possible, but substitutions can be made, occasionally with a change of seals.

Arctic hydraulic fluids are available (usually 10W) with a useful range down to about –60°C or less, and may be mineral, synthetic or silicone based. Aviation hydraulic fluid is often used in the extreme cold, but it should be replaced when warmer weather returns. Fluids commonly used by Arctic operators also include automatic transmission fluid and synthetic multigrade engine oils.

These engine oils can be used all year provided they satisfy the SAE 20 requirements at 100°C shown in Table 2.

The critical factor in fluid selection is the pump, which is designed to work most efficiently with fluids in a certain viscosity range. If the fluid is too thin, the pump may overheat or suffer mechanical damage; if it is too thick, the pump may cavitate.

It is generally recommended that when a cold-soaked hydraulic system is to be used it should first be exercised. This merely means extending and retracting it a few times slowly with no load so that the oil can be warmed and circulated throughout the system. In most cases this will eliminate or reduce problems with seal damage and leakage. Larger equipment will take longer than smaller machines because of the larger volume of fluid that must be warmed. Once the hydraulics have been warmed sufficiently to operate normally, there should be no further problems. An exception to this is equipment in which some cylinders are not constantly used, such as graders, where the blade will be set at the desired position and not called upon to move for an extended period. In this case the fluid may stiffen during operation such that the idle cylinders must be treated as cold-soaked when finally used. Equipment such as bulldozers, loaders and forklifts usually do not have this problem since all hydraulic components are in constant use. In some cases it may be desirable to insulate or heat the hydraulic reservoir or both, but this is not a widespread practice.

Certain equipment, such as cranes, pose a more difficult problem since the fluid in the outermost rams is continuously exposed to low ambient temperatures and cannot readily be returned to the relatively warm reservoir. In these extreme cases, aviation hydraulic fluid is often used because of its excellent low-temperature properties. However, its very low viscosity may result in a certain amount of leaking, and it is also a poor lubricant and may cause excessive wear in the pump. It may also cause damage to certain types of seals and should therefore be used only when necessary.

Power steering fluid

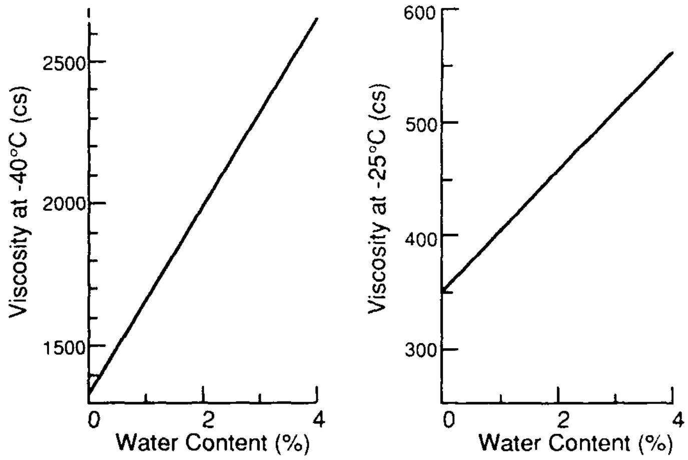
As with automatic transmission fluids, many fluids are available for this application, including many multigrade synthetic motor oils, automatic transmission fluid, silicone products and even such fluids as kerosene. The principal problems with power steering systems are associated with their use immediately on start-up. If sharp turns are executed when the fluid is very cold, the pump is forced to operate at its maximum capacity with an excessively viscous material. This may result in cavitation or pump damage; moreover, the high pressures generated under these conditions commonly cause damage to seals and hoses, with consequent leaks.

Brake fluid

Most commonly used brake fluids are mixtures of polyglycol ethers and polyglycols. Since it appears to be virtually impossible to exclude water contamination in brake systems, these fluids are normally used to prevent moisture from collecting and causing corrosion and freezing problems. They can be used down to –40°C. However, because they are hygroscopic, they may increase their moisture content up to about 2% per year. This results in an increase in their low-temperature viscosity, as shown in Figure 2. Easy braking is reportedly achieved at viscosities up to about 1000 cs.

Both mineral oil and silicone brake fluids are commercially available. These fluids are usually designed to meet the requirements of particular brake system manufacturers and may not be suitable for all brake systems. MIL-B-46176 is a silicone fluid useful down to –55°C. Silicone fluids are not hygroscopic and are reportedly also superior to the glycol types in that they tend to keep the seals more flexible at low temperatures. They are not compatible with the glycol-based fluids, and mixing these different types may damage the seals because of the reaction between the two.

Other fluids, such as kerosene, have sometimes been used in brake systems at low temperatures. However, it is generally best to use fluids designed or recommended for the job.



a. Viscosity behavior at –40°C. b. Viscosity behavior at –25°C.

2. Effect of moisture content on the viscosity of polyglycol fluids. (After Klamann 1984.)

Wire rope lubrication

Wire rope is normally lubricated during manufacture and should be relubricated fairly frequently during normal operation. Lubricants normally used are high-molecular-weight hydrocarbons, which provide satisfactory service in temperate regions. However, in

viscosity at 100°C and at various lower temperatures depending on the viscosity grade. There are 10 such grades as shown in Table 2.

extremely cold conditions these compounds become stiff to the point where it becomes difficult to flex the rope, as through a pulley or sheave, and the lubricant may flake off, leaving the individual strands of the rope unprotected from wear, abrasion, corrosion and rust.

Wire rope is constructed by bending a number of wires in a helical pattern around a single central wire to form a single strand. A number of these strands are then similarly bent around a central core, usually fibrous (e.g. sisal) or plastic (e.g. polypropylene), to form the wire rope. During manufacture this soft core is saturated with lubricant, and later it serves both as a reservoir for lubricant for the wires and as a cushion to prevent nicking and pinching of the innermost wires.

In the absence of adequate lubrication, the life of a wire rope is much diminished. Rust and corrosion may become a serious problem. Increased wear, abrasion and fatigue are likely; the latter is one of the main causes of rope failure and is exacerbated by the increased frictional resistance to movement of the wires over one another as the rope flexes.

Lubricants must be able to penetrate through the wires to the core and provide protection to both. There are commercially available silicone fluids that may be useful in this application, as well as PTFE dispersions.

General considerations

In all cases, if the technical literature provided by the equipment manufacturer does not specifically approve a particular Arctic-grade fluid for use in their machinery, it is best to discuss the substitution with them to try to identify the best compromise. In some cases a simple alteration such as changing the seals may be enough to allow use of a suitable fluid. If a satisfactory suggestion cannot be obtained from the manufacturer, then the alternative is to use a low-viscosity fluid with an additive package as close as possible to that specified and send samples of the fluid for lab analysis at frequent intervals to ensure that excessive wear is not taking place.

If heat is applied to ensure adequate lubricant fluidity, such as on the oil pan or transmission, the rate of heat transfer should not be greater than about 2 or 3 W/cm^2. Since oil is a poor thermal conductor, local overheating may degrade the oil by thermal breakdown and oxidation.

It is a good idea to lubricate vehicles immediately after operation when the working parts are still warm and maximum penetration of lubricants will result.

References

Booser, E.R. (ed.) (1984) *CRC Handbook of Lubrication (Theory and Practice of Tribology). Vol I & II.* Boca Raton, Florida: CRC Press.

Bugelski, W.G. (1975) Preparation and operation of diesel engines in construction and industrial machinery for operation in cold climates. *SAE Transactions*, **84**(2): 1273–1289.

Caterpillar (1987) *Operations and Maintenance: Cold Weather Recommendations for Caterpillar Machines.* Caterpillar, Inc., SEBU589-03.

Chevron USA, Inc. (1988) *Product Salesfax Digest.* Product Line Management/Technical Support, Chevron USA, Inc., San Francisco, California.

Department of Defense (1989) Guide for the selection of lubricants, functional fluids, preservatives and specialty products for use in ground equipment systems. DOD Military Handbook, MIL-HDBK-113C.

Frame, E.A., A.F. Montemayor and E.C. Owens (1989) Low-temperature pumpability of US Army diesel engine oils. SAE Technical Paper No. 892053, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania.

Jacobson, M.M. (1964) Materials engineering for cold regions and the brittle fracture problem. *Science in Alaska—Proc., 15th Alaskan Science Conference, College, Alaska, Aug. 31–Sept. 4, 1964.* Also in *American Association for the Advancement of Science*, Mar. 15, 1965.

Johnson, R.S. (1984) Laboratory engine test study of motor oil flow properties in winter service. *SAE Transactions*, **93**(6): 6.81–6.93

Klamann, D. (1984) Lubricants and related products: Synthesis, properties, applications, international standards. Verlag Chemie, Deerfield Beach, Florida.

Lestz, S.J., E.C. Owens and T.C. Bowen (1989) Army arctic engine oil performance in high ambient temperatures. SAE Technical Paper No. 892051, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania.

Machleder, W.H. and R.J. Kopko (1989) Low temperature pumpability studies in a heavy-duty diesel engine, Part II. SAE Technical Paper No. 890240, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania.

May, C.J., and J.J. Habeeb (1987) Factors affecting the low temperature pumpability of used engine oils. *SAE Transactions*, **96**(7): 7.298–7.306.

Newton, W.S. and C.G. Makrides (1954) Effect of climate and environment on ground support equipment. Corvey Engineering

Co., Report to Air Research and Development Command, USAF, Wright-Patterson Air Force Base, Ohio, Technical Report 54-132.

Robertson, W.S. (ed.) (1984) *Lubrication in Practice*. ESSO Petroleum Company Ltd. New York: Marcel Dekker.

Roth, R.J.G. (1989) Requirements of diesel engine oil as it relates to low temperature operation. SAE Technical Paper No. 890993, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, Pennsylvania.

Stambaugh, R.L. (1984) Low temperature pumpability of engine oils. *SAE Transactions*, **93**(6): 6.94–6.101.

Stupich, T.F. (1987) Cold regions operation of diesel vehicles with special consideration for the M113A1 Armoured Personnel Carrier. Defense Research Establishment Suffield, Ralston, Alberta, Suffield Report No. 408.

Union Carbide (1982) *Silicone Fluids*. Union Carbide Corporation, Silicones and Urethane Intermediates, Danbury, Connecticut.

U.S. Army (1989) U.S. Army operation and maintenance of ordnance materiel in cold weather (0°F to –65°F). Department of the Army, FM 9-207.

U.S. Navy (1988) U.S. Navy polar operations manual. Naval Sea Systems Command, S0300-A5-MAN-010.

Wills, J.G. (1980) *Lubrication Fundamentals*. Mobil Oil Corp. New York: Marcel Dekker.

Appendix A: API engine oil classifications. (From Chevron USA, Inc. 1988.)

The American Petroleum Institute (API) engine oil classification system was set up as a joint effort by API, ASTM (American Society for Testing and Materials) and SAE (Society of Automotive Engineers). This letter classification system is a method of classifying engine oils according to their performance characteristics and related to their intended type of service. The API Engine Oil Classifications can be broken into the following.

Letter Designation	*API Engine Service Description*	*ASTM Engine Oil Description*
SA	***Utility Gasoline and Diesel Engine Service*** Service typical of engines operated under such mild conditions that the protection afforded by compounded oils is not required. This classification has no performance requirements.	Oil without additive except that it may contain pour and/or foam depressants.
SB	***Minimum-Duty Gasoline Engine Service*** Service typical of engines operated under such mild conditions that only minimum protection afforded by compounding is desired. Oils designed for this service have been used since the 1930s and provide only antiscuff capability and resistance to oil oxidation and bearing corrosion.	Provides some antioxidant and antiscuff capabilities.
SC	***1964 Gasoline Engine Warranty Maintenance Service*** Service typical of gasoline engines in 1964–1967 models of passenger cars and trucks operating under engine manufacturers' warranties in effect during those model years. Oils designed for this service provide control of high- and low-temperature deposits, wear, rust and corrosion in gasoline engines.	Oil meeting the 1964–1967 requirements of the automobile manufacturers. Intended primarily for use in passenger cars. Provides low-temperature antisludge and antirust performance.
SD	***1968 Gasoline Engine Warranty Maintenance Service*** Service typical of gasoline engines in passenger cars and trucks beginning with 1968 models and operating under engine manufacturers' warranties. Oils designed for this service provide more protection from high- and low-temperature engine deposits, wear, rust and corrosion in gasoline engines than oils for API Service Classification SC and may be used when oils for API Service Classification SC are recommended.	Oil meeting the requirements of the automobile manufacturers since 1968. Intended primarily for use in passenger cars. Provides low-temperature antisludge and antirust performance.
SE	***1972 Gasoline Engine Warranty Maintenance Service*** Service typical of gasoline engines in passenger cars and trucks beginning with 1972 models operating under engine manufacturers' warranties. Oils designed for this service provide more pro-	Oil meeting the 1972 requirements of the automobile manufacturers. Intended primarily for use in passenger cars. Provides

Letter Designation	API Engine Service Description	ASTM Engine Oil Description
SE	***1972 Gasoline Engine Warranty Maintenance Service (cont'd)*** tection against oil oxidation, high-temperature engine deposits, rust and corrosion in gasoline engines than oils which are satisfactory for API Service Classification SD or SC and may be used when either of these classifications is recommended.	high-temperature antioxidation, low-temperature antisludge and antirust performance.
SF	***1980 Gasoline Engine Warranty Maintenance Service*** Service typical of gasoline engines in passenger cars and some trucks beginning with 1980 models operating under engine manufacturers' recommended maintenance procedures. Oils developed for this service provide increased oxidation stability and improved antiwear performance relative to oils which meet the minimum requirements for API Service Classification SE. These oils also provide protection against engine deposits, rust and corrosion. Oils meeting API Service Classification SF may be used where API Service Classifications SE, SD or SC are recommended.	Engine manufacturer maintenance service classification for gasoline engines beginning with 1980 model passenger cars.
SG	***1988 Gasoline Engine Warranty Maintenance Service*** Service typical of gasoline engines in passenger cars and some trucks beginning with 1989 models operating under engine manufacturers' warranties. This API engine classification requires oils to demonstrate improved sludge and varnish control, better oxidation control and improved wear performance for gasoline service. SG introduces two new severe engine tests which provide improved quality over SF oils. SG incorporates the current diesel engine test required for API Service Classification CC. Oils meeting API Service Classification SG may be used where API Service Classifications SF, SE, SD or SC are recommended.	Engine manufacturer maintenance service classification for gasoline engines beginning with 1988 model passenger cars.
CA	***Light Duty Diesel Engine Service*** Service typical of diesel engines operated in mild to moderate duty with high-quality fuels. Occasionally has included gasoline engines in mild service. Oils designed for this service were widely used in the late 1940s and 1950s. These oils provided protection from bearing corrosion and from high-temperature deposits in normally aspirated diesel engines when using fuels of such quality that they impose no unusual requirements for wear and deposit protection.	Oil meeting the requirements of MIL-L-2104A. For use in gasoline and naturally aspirated diesel engines operated on low-sulfur fuel. The MIL-L-2104A specification was issued in 1954.
CB	***Moderate Duty Diesel Engine Service*** Service typical of diesel engines operated in mild to moderate duty but with lower-quality fuels which	Oils for use in gasoline and naturally aspirated diesel en-

Letter Designation	*API Engine Service Description*	*ASTM Engine Oil Description*
	Moderate Duty Diesel Engine Service (cont'd) necessitate more protection from wear and deposits. Occasionally has included gasoline engines in mild service. Oils designed for this service were introduced in 1949. Such oils provide necessary protection from bearing corrosion and from high-temperature deposits in normally aspirated diesel engines with high-sulfur fuels.	gines. Includes MIL-L-2104A oils where the diesel engine test was run using high-sulfur fuels.
CC	***Moderate Duty Diesel and Gasoline Engine Service*** Service typical of lightly supercharged diesel engines operated in moderate to severe duty and has included certain heavy duty gasoline engines. Oils designed for this service were introduced in 1961 and used in many trucks and in industrial and construction equipment and farm tractors. These oils provide protection from high-temperature deposits in lightly supercharged diesels and also from rust, corrosion and low-temperature deposits in gasoline engines.	Oil meeting requirements of MIL-L-2104B. Provides low-temperature antisludge, antirust and lightly supercharged diesel engine performance. The MIL-L-2104B specification was issued in 1964.
CD	***Severe Duty Diesel Engine Service*** Service typical of supercharged diesel engines in high-speed, high-output duty requiring highly effective control of wear and deposits. Oils designed for this service were introduced in 1955 and provide protection from bearing corrosion and from high-temperature deposits in supercharged diesel engines when using fuels of a wide quality range.	Oil meeting Caterpillar Tractor Company certification requirements for Superior Lubricants (Series 3) for Caterpillar diesel engines. Provides moderately supercharged diesel perfomance. The certification of Series 3 oil was established by Caterpillar Tractor Company in 1955.
CD-II	***Severe Duty Two-Stroke Cycle Diesel Engine Service*** Service typical of two-stroke cycle diesel engines requiring highly effective control over wear and deposits. Oils designed for this service also meet all performance requirements of API Service Category CD.	Oil meeting current API CD specification and performance. Includes MIL-L-2104D (DDA 6VE-53T Specification). Measures wear and deposits for 2-cycle engine.
CE	***Severe Duty Diesel Engine Service*** CE adds three modern multicylinder diesel engine tests to the existing CD category. These multicylinder tests are the Cummins NTC 400, Mack EO-K and Mack EO-K/2 specification tests. API Service Classification CE requires oils to demonstrate improved oil consumption, wear, deposit and viscosity control. These features are essential for modern direct-injection, turbocharged engines.	Oil meeting requirements for evaluating oil consumption, wear and deposits due to soot and oil oxidation along with previous requirements of CD.

Abbreviations

API	American Petroleum Institute
BPT	Borderline pumping temperature
CCS	Cold cranking simulator
DI	Detergent inhibitor
MRV	Mini-rotary viscometer
NLGI	National Lubricating Grease Institute
PAO	Poly-α-olefin
PPD	Pour point depressant
PTFE	Polytetrafluoroethylene (Teflon)
SAE	Society of Automotive Engineers
VI	Viscosity index
VII	Viscosity index improver

Temperature conversion scale